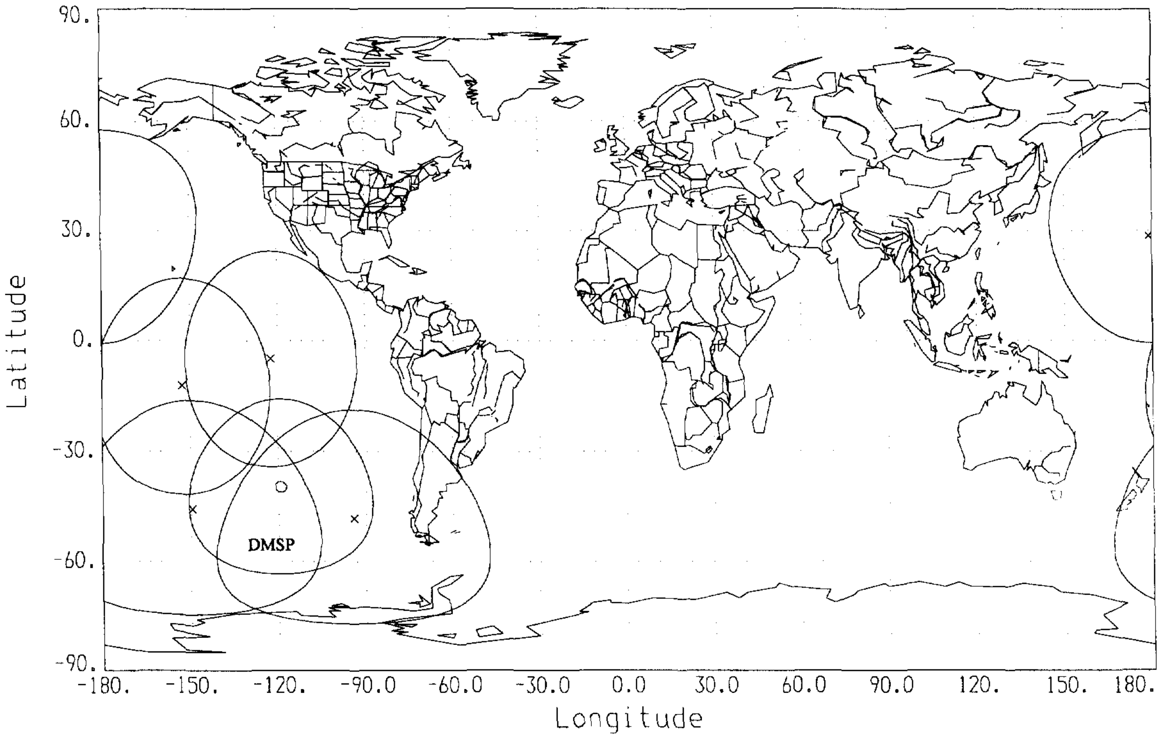

Figure 24. Leo One USA Interference Footprint Overlaps With DMSP At 80 Minutes.

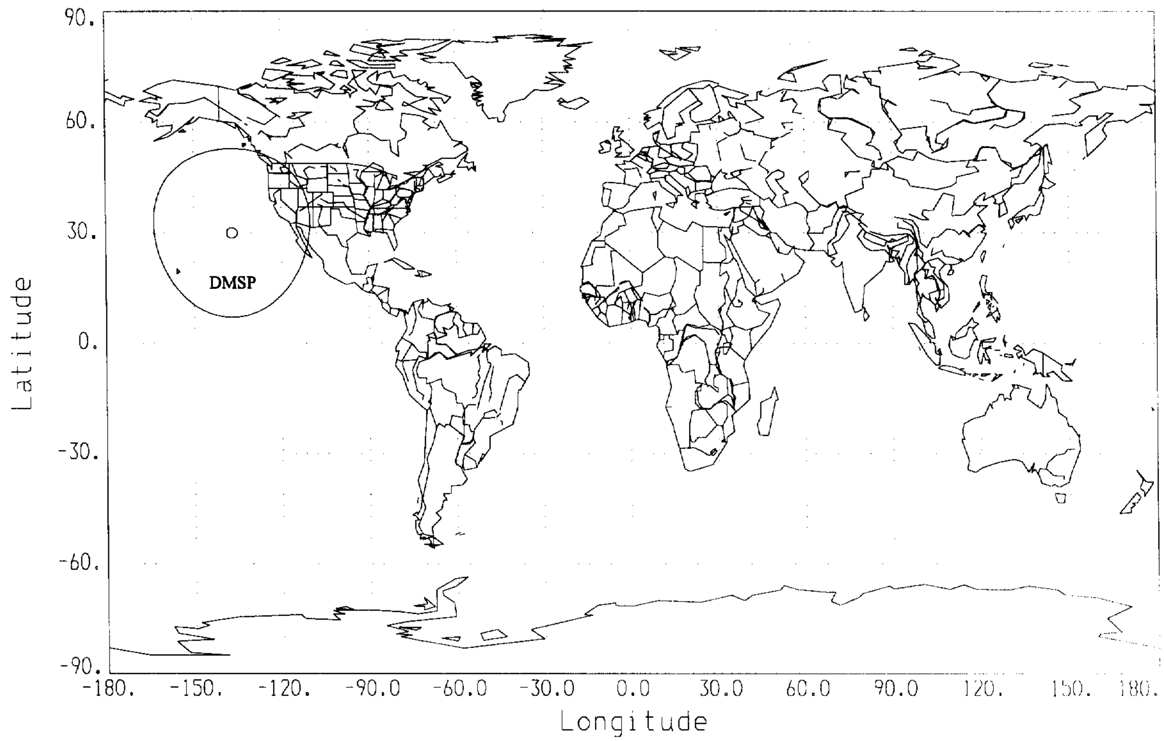

Figure 25. Leo One USA Interference Footprint Overlaps With DMSP At 100 Minutes.

2.D.3 "90 Minute" Site Results

Figure 26 shows the Leo One USA satellite command times for the "90 Minute" command sites using a 10° minimum elevation angle. This figure starts from the DMSP Sunnyvale contact time and assumes commanding of the Leo One USA satellites begins immediately as they contact the command stations. This result is for the five 90 minute command site locations. As shown, for this particular starting time, all satellites are commanded within 60 minutes. Again, the potential interference times are given by Figure 27.

Figure 27 shows the timeline for footprint overlap conflicts as a function of time. As indicated, after approximately 53 minutes all of the conflicting Leo One USA satellites have been commanded to their new frequency assignments. After 40 minutes the area impacted is small.

Figure 28 shows the extent of the DMSP coverage footprint overlap at 20 minutes and Figure 29 shows the coverage overlap at 40 minutes. As indicated, the loss in coverage area for the DMSP satellite shrinks dramatically after approximately 40 minutes and is grouped in one longitude zone. Again, all satellites have not been commanded until 60 minutes have elapsed in this example.

These limited simulation examples are intended to indicate the nature of the transitional interference. Many variations are possible. However, the results presented here are believed to be representative. Again, it would seem that the one orbital period update time would be adequate for most all purposes. More importantly, all interference can be avoided through pre-planned and coordinated frequency changes.

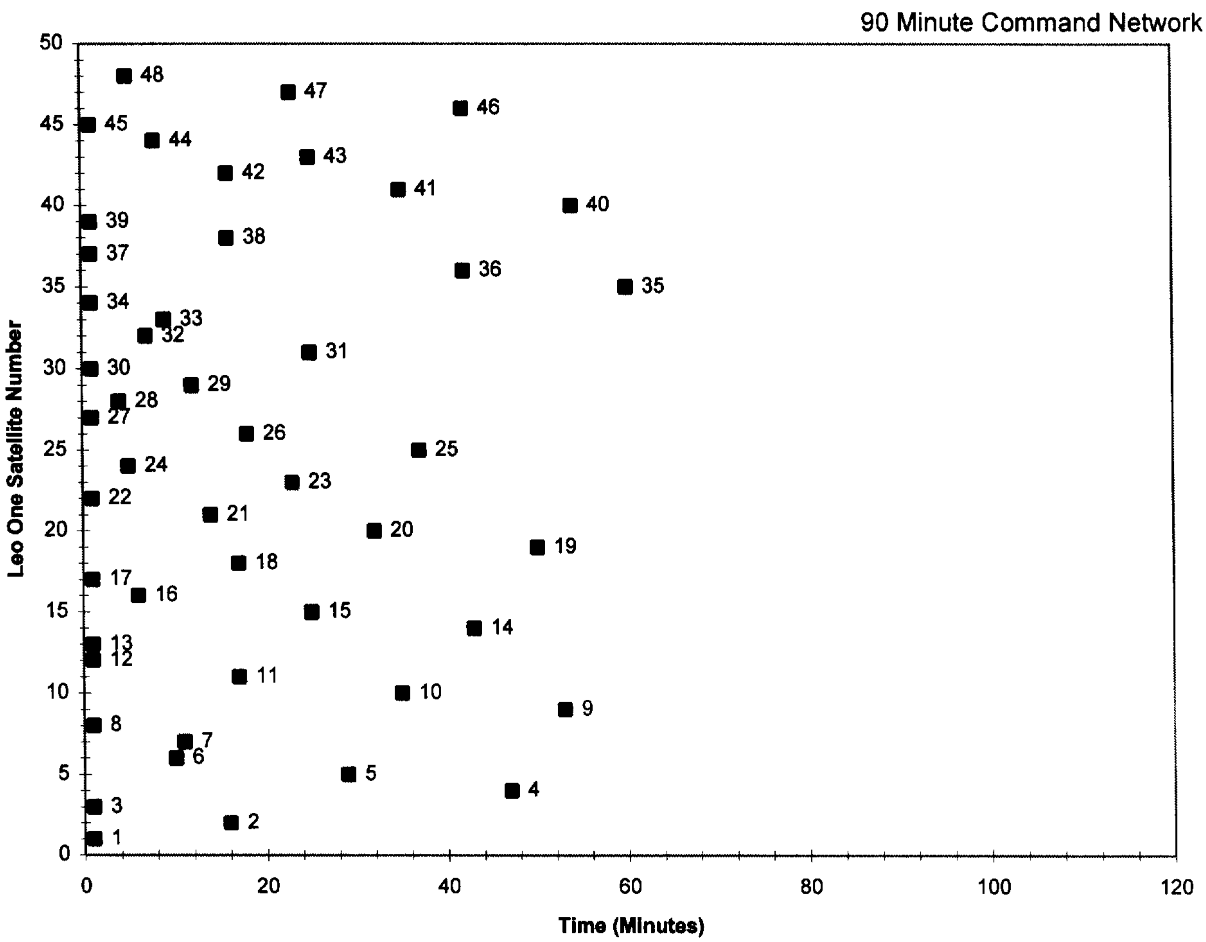

Figure 26. Leo One USA Satellite Command Times With "90 Minute" Command Sites.

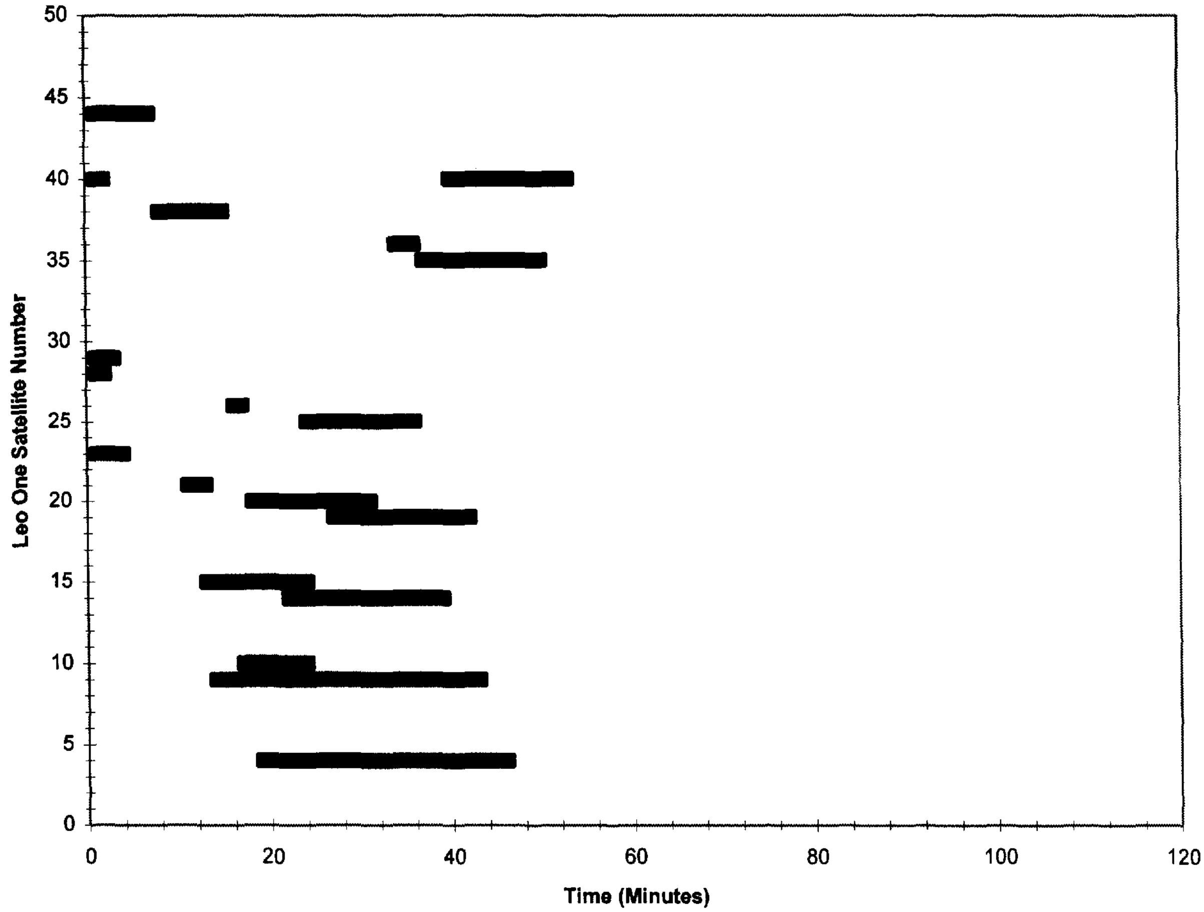

Figure 27. Transitional Interference Times To DMSP Using "90 Minute" Command Sites.

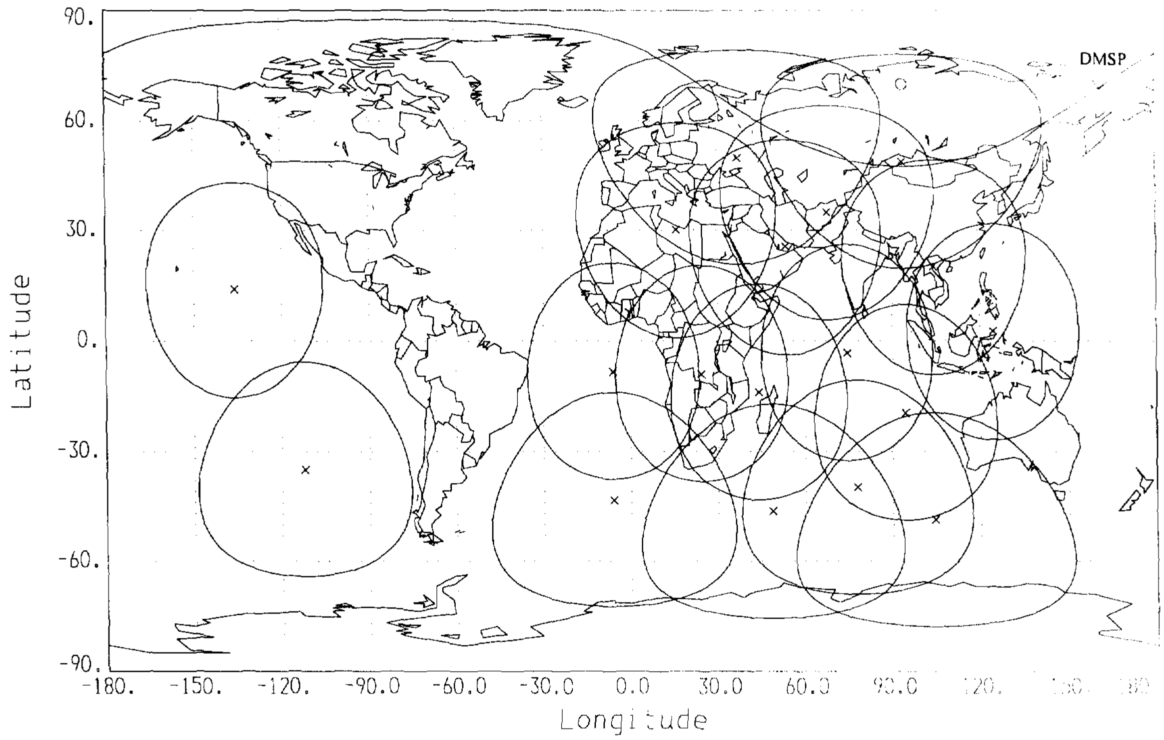

Figure 28. Leo One USA Interference Footprint Overlaps With DMSP At 20 Minutes - "90 Minute" Command Sites.

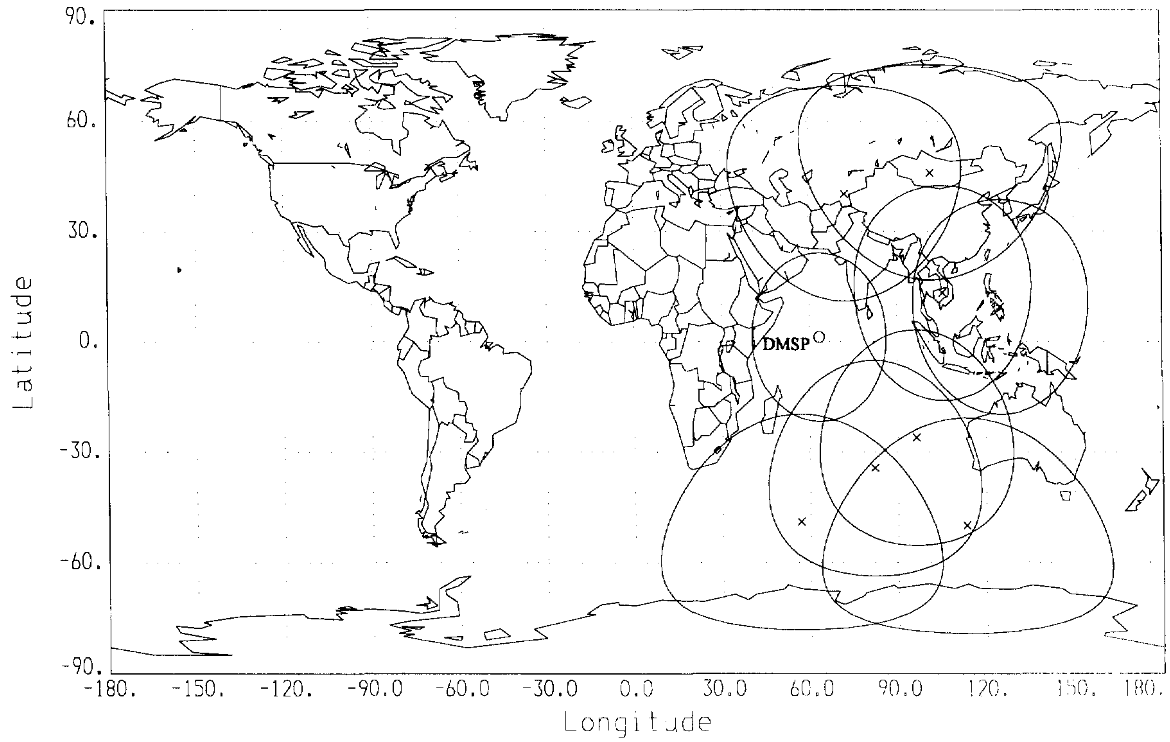

Figure 29. Leo One USA Interference Footprint Overlaps With DMSP At 40 Minutes - "90 Minute" Command Sites.

E. Accurate Ephemeris Prediction

There are two parts to the prediction of potential coverage overlaps of DMSP satellites with a Little LEO constellation coverage footprints. The first part deals with the determination of the satellite orbit element sets (or ephemeris) and the second part deals with the forward propagation of this element set to future locations of these satellites. This prediction accuracy determines the need to grow the exclusion radius to guarantee no interference to DMSP. Here we assume the defined exclusion radius has been defined in terms of the necessary minimum elevation angle contours from the DMSP and Little

LEO satellites. The prediction uncertainty then effectively adds to the required DMSP exclusion radius. For instance, 10 km in coverage location uncertainty would increase a 5 degree elevation angle coverage exclusion zone from 2612.9 kilometer radius to 2622.9 kilometers on the surface of the earth. This is equivalent to a 4.89 degrees elevation coverage exclusion zone for DMSP instead of 5.0 degrees. This difference is not significant in terms of the availability impact to Little LEO coverage.

The orbit determination process accuracy is a function of the observation interval and the accuracy of the observables (range and elevation angle for NORAD radar tracking) and the sparseness of the observations. Typically, commercial satellites and most DoD satellites provide their own orbit determination through ranging from surveyed ground sites. Newer and potentially more accurate near real time approaches have evolved through the use of GPS. Point positioning with GPS is as accurate in low orbit as on the ground, typically 50 to 100 meters[5] for single frequency C/A code users with nominal levels of GPS selective availability (a degradation imposed by DoD on GPS civil user accuracy). Corresponding velocity estimates may approach 0.5 m/s accuracy. The accuracy achieved is a function of the receiver design and care taken in time tagging data.

These instantaneous measurements, however, may be inadequate for orbit prediction purposes. Classical dynamic orbit determination exploits orbital mechanics and filtering theory to yield a stable and accurate orbit solution from generally sparse and noisy measurements. This approach is required for conventional tracking systems. In dynamic orbit determination, the orbit model is derived from models of the forces acting

---

[5] T. Yunck, "Orbit Determination", Global Positioning System: Theory and Applications. Vol. II, AIAA Vol. 164, 1996, pp 559-589.

on the satellite and the laws of motion. Highly accurate models include the satellite physical properties. The major forces include gravity, aerodynamic drag and lift, solar radiation pressure, and active thrusting (once or twice per orbit). Lesser contributions may come from outgassing, satellite thermal radiation, sunlight reflected from the Earth, and electromagnetic effects. The force and satellite models are used to compute a model of satellite acceleration over time, from which by double integration, a nominal trajectory is formed. In principle, all that is required to produce the orbit solution is to determine the two vector constants of integration, position and velocity, at one time point. This is done through an estimation procedure that finds the best estimate of this epoch state (usually through minimizing the mean square fitting error) for which the resulting model trajectory best fits the tracking data according to some optimality criterion.

NASA has developed what has been termed kinematic solution approaches that enable much more precise orbit determination using GPS measurements. For instance, predictions with the space shuttle has shown the 3-D position error of 43 meters using dynamic solutions, 28 cm with single frequency kinematic solutions and 3 cm with dual frequency kinematic solutions after 8 hours of arc measurements[6]. The achievable accuracy using direct real-time GPS approach is shown in the figure below (Figure) which is a function of orbit altitude. Actual performance will depend on specifics of the GPS tracking configuration and satellite dynamics, but the figure does indicate that

[6] T. Yunck, "Orbit Determination", Global Positioning System: Theory and Applications. Vol. II, AIAA Vol. 164, 1996, p 588.

satellite location techniques are available that are more than adequate for interference avoidance requirements.

We would recommend the commission not dictate a required method, as virtually all reasonable approaches should be more than adequate for interference avoidance. Depending upon the method chosen and the resulting accuracy, the coverage error radius must be adjusted accordingly. This can be coordinated with NOAA to mutual satisfaction.

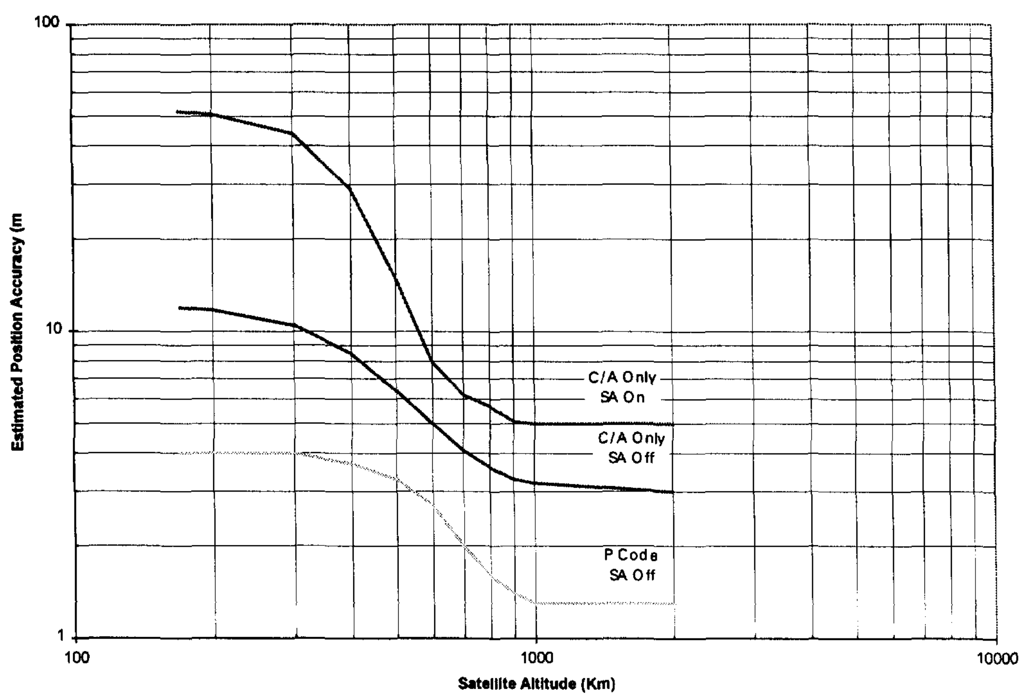

Figure 30. Estimated Orbit Accuracy's Achievable Using Real-Time Direct GPS Techniques[7].

[7] Adapted from T. Yunck, "Orbit Determination", Global Positioning System: Theory and Applications. Vol. II, AIAA Vol. 164, 1996, p 588.

The second part of the problem is the forward time projection of position location assuming no further real-time data is available following an element set estimation. This is accomplished through the use of orbit propagators. Orbit propagation can be accomplished through analytical or numerical methods. The more advanced and accurate methods will use numerical integration to generate the ephemeris. Numerical methods include the perturbation effects from the earth's oblateness, atmospheric drag (drag as a function of altitude and temperature), sun-lunar perturbations, solar radiation effects, and other large body effects (i.e., Jupiter, moon, etc.) Generally, the Cowell method is the choice of numerical methods to be used by propagators. The following are some propagators using numerical methods that are commercially available.

- *Orbital Workbench*: This is a fairly accurate tool that uses the Cowell method. It has been used on DoD projects to verify NORAD data within 100 meters. This tool is over 5 years old and the newer version is even more accurate with updated atmospheric drag tables. However, the latest version is still in a beta form and not ready for release.

- *WS/PODS*: This tool is another Cowell numerical integrator that has accuracies within 1.0 meter of the true orbit with a fitting accuracy of 10 cm. PODS is a very reliable tool and takes into consideration all of the gravitational forces. It is an active tool that allows and performs updates to the drag tables. The tool is flexible enough that the integration step size and force models can be changed and updated. LEO-One has this tool currently running under STK, but it can also run as a stand alone batch file. The difference is that the batch file does not have the pretty graphics that STK has. The stand alone is approximately $10,000 and the STK is $20,000. GPS-MET is using this tool currently.

- *HPOP:* This propagator uses a 7th order Runge-Kutta method to propagate its orbit. It is accurate to within 10 meters of the original orbit. This tool is run under STK and costs approximately $20,000.

Analytic methods are also used to perform orbit propagation. These methods are not as accurate as numerical and usually do not include perturbation effects except the J2 effect. The following are analytic propagators:

- *Astrovis*: The best propagator that this tool has is determining the Keplerian orbit with the J2 effect included. Not realistic for use with any kind of accuracy.

- *PCSOAP*: This tool has different propagators. It uses the SGP, SGP4 and SDP4 NORAD propagators that are old and not very accurate. It also uses the Keplerian propagator like Astrovis but states a disclaimer that they will not guarantee its accuracy past 24 hours. They also mention a Low Thrust propagator that includes most perturbation effects. Not all that advanced from Astrovis.

If the accuracies that NOAA/DMSP/DoD requires of Leo One USA are very tight then it is reasonable to choose a tool that uses a numerical integration method to propagate the orbit. The costs can be high, however. All the propagators are set up to read two-line element sets as well as state vectors and propagate accordingly.

It is our understanding that NOAA and DMSP currently rely on NORAD radar tracking for orbit determination and SGP4 propagators using mean two line element set for prediction. We would recommend that more precise orbit determination and prediction means be used in the future. NORAD's prediction techniques are typically not very accurate, especially when using a mean two line element set. NORAD's requirement for NOAA is typically set to predict within an accuracy of 5 km with 90 percent confidence. As a result of this requirement, the period over which the predicted orbit is accurate is typically two weeks. The accuracy of orbit propagation is dependent upon the accuracy of the orbital elements provided by the tracking system (observables), the precision to correct the orbital emements for errors (orbit determination), and the precision of predicting the spacecraft's orbit (orbit propagation). This is discussed further below.

Observables

NORAD tracks satellites from various ground stations that obtain azimuth, elevation, range, and range rate data. The observable's require multiple passes to determine its orbit within an accuracy of 5 km. The observables obtained from each of the ground stations are different due to location, environment, and equipment. The errors incurred from a station are weighted and factored into the orbit calculations for the different satellite observables. As a result, these errors are propagated with the orbit and affect the length of period for which a predicted orbit is good.

Satellite ranging provides an alternative method for generating observable data. This approach has been performed so long that a reliable system can achieve accuracies less than 1 meter.

Orbit Determination

NORAD uses the satellite observables to generate a Two Line Mean Element Set (2LMES). A mean element set is defined as the motion of the orbit over a span of time. When taking data over a period of time and averaging the data, the element set is no longer defining the true orbit, but some integral of it. Therefore, the orbit that is propagated is not the true orbit.

For more precise orbits an osculating element set is used. Osculating elements describe a true Keplerian orbit instantaneously tangent to the motion of the true orbit. For instance, GPS tracking data can provide a State Vector for the orbit determination method. The state vector is the position and velocity of the spacecraft at an instant in time. Having the true orbital element set of a satellite at an instant in time incurs no errors, as compared with NORAD's mean set of elements.

The 2LMES is generated using a differential corrections scheme, simply Newton's method. Newton's method is a "quick and dirty" calculation that provides adequate results. NORAD uses historical data to help correct the elements by comparing it to actual orbit data and predicted data. This must be done to compensate for the mean elements.

Numerical integration generates more accurate element sets for osculating elements using Predictor-Corrector methods (i.e., weighted least squares). These methods correct for the position errors, including the weighted errors from the ground station. For GPS, the result is a postion vector typically within 20 m of its actual position as discussed previously.

Orbit Propagation

If NORAD propagates it's 2LMES analytically, typically with SPG4, all the errors from the observables are propagated with the elements, as described above. As a result, the length of time that a satellite's orbit can be propagated is based on the position tolerances required for the satellite and how fast the errors propagate.

Given more accurate observables (as described above), numerical integration can propagate the satellite's orbit for longer periods of time. One highly accurate method for propagation is Cowell's method as described above. Cowell's method numerically integrates the orbit's motion and perturbation accelerations at the same time. The accuracy obtained for this method is within 100 meters of the true orbit for as long as 2 to3 weeks for LEO satellites.

It is recommended that the use of NORAD's 2LMES be avoided as providing low orbit prediction accuracy. A state vector or a ranging approach is recommended as the format for obtaining the observables. The element set should use numerical integration to perform both orbit determination and orbit propagation (Cowell's method). The result can be orbit prediction within 100 meters of the actual orbit for a period longer than two weeks. Moreover, there are good orbit determination and propagation COTS tools available today. These tools can and will be utilized to perform Leo One USA's orbit calculations.

3. Sharing With the Radio Navigation Satellite Service

NVNG MSS systems can share with RNSS satellite systems. However, this sharing will impose certain burdens on the NVNG MSS operator. The fact that the U.S. Transit satellite system will have vacated the Transit band by the end of 1996 is of little consequence when considering the significant interference imposed by the Russian RNSS satellite system to Little LEO satellite uplink receivers. The ITU working groups have concluded that sharing between maritime and aeronautical MSS stations (Earth to Space) with existing RNSS systems in the 149.95 - 150.05 MHz and 399.9 - 400.05 MHz bands is impractical because of the required coordination distances.[8] It also concludes the MSS

[8]The coordination distances required range from 180 to 360 km for subscriber terminals and up to 660 km for gateways. See "Methodology Of Estimating Feasibility Of Sharing Between MSS Systems and Existing RNSS Systems in the Frequency Bands 149.-150 MHz and 399.400.05 MHz", ITU Doc. 8D/TEMP/123-E, 5 Nov. 1996.

LEO spaceborne receivers will be subject to strong interfering signals from these Russian Navsats (Their altitude is 1000 km, 83° inclined, passing in close proximity to Leo One USA's satellites at 950 km altitude). The Russians have indicated their intention to maintain 10 navigation satellites, one in each of 10 orbit planes. Because the signals from these satellites span the proposed System 3 uplink band and interfere with uplink reception, any Little LEO system would frequently have to shut down or avoid these signals during each orbital revolution.

In general, the best strategy for sharing this band appears to be to step around those RNSS satellite frequencies in the Little LEO horizon. Figure 31 shows the RNSS satellites in-view of a Leo One USA satellite (Satellite 5/1) as a function of time, shown here over 24 hours (a day in the life of a Leo One USA satellite).

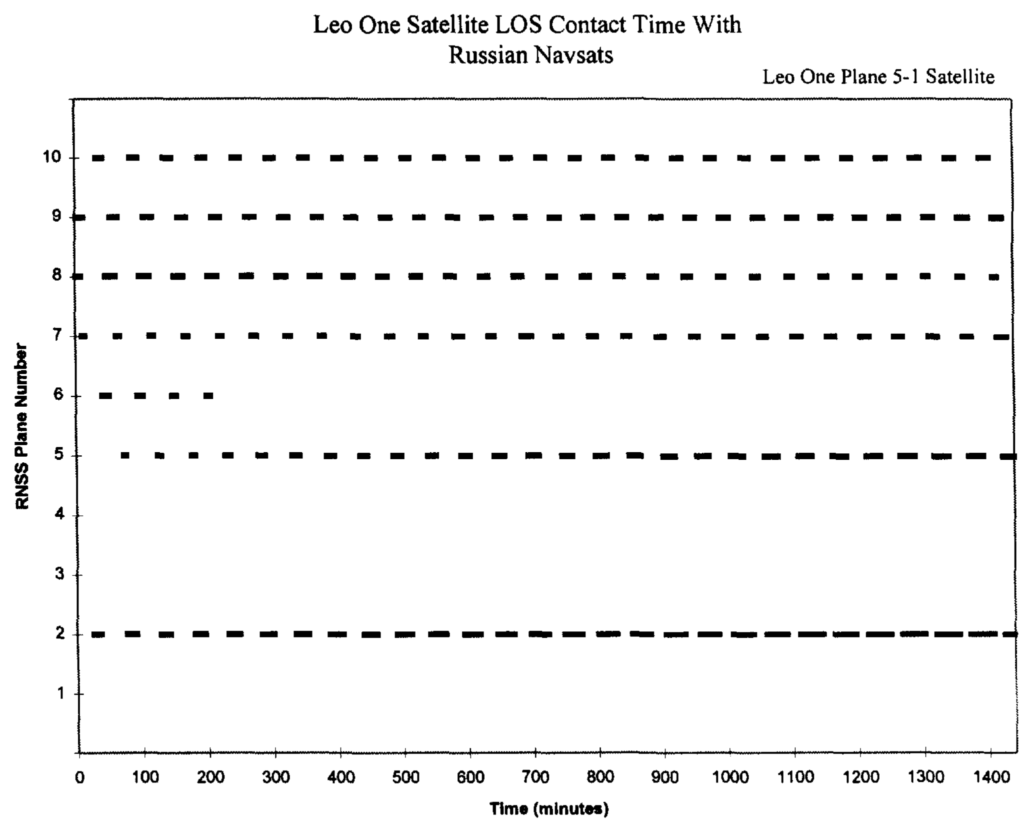

Figure 31. RNSS Interference Intervals To One Leo One USA Satellite Over One Day

A variety of different contact situations can occur. There are other situations where a Leo One USA satellite travels within the horizon of an RNSS satellite for over a day. Note the repetitive nature of the recontact time of approximately twice per rev for many of the RNSS satellites shown in this figure. As shown, at times there are as many as 5 RNSS satellites in a Leo One USA satellite radio horizon at one time. This has the potential of blocking the entire band proposed for System 3 for a significant percentage of time. Thus, the true capacity of the available 100 kHz bandwidth will be considerably reduced and has been determined to be less than 50% of what would be available with otherwise clear spectrum. Sharing of this limited band capability is extremely difficult because of the limited spectrum and the dynamic time varying nature of the useable spectrum during each orbital revolution. Nevertheless, with proper satellite design, the use of good engineering practices and a suitable channel assignment plan it should be possible for an NVNG MSS system to use the 149.95-150.05 MHz band.

APPENDIX F

APPENDIX F

PERFORMANCE ATTRIBUTES OF PROPOSED SYSTEM A AND SYSTEM B

1.1 Introduction

The spectrum assignments proposed in the Notice for System 1, System 2 and System 3 do not make efficient use of the available spectrum, will not support economically viable competitors, cannot serve maritime and aeronautical markets, and cannot provide near real-time performance. Leo One USA recommends an alternative proposal that maximizes the efficient use of the spectrum and supports two economically viable systems: System A and System B. The following discussion of the performance of these new proposed systems shows near real-time performance is possible. In Appendix B, Leo One USA demonstrated that Systems A and B provide up to 90 and 92 percent of the capacity of Orbcomm, respectively. Equally important, both System A and System B are able to serve land, maritime and aeronautical markets, effectively fostering competitive NVNG MSS services. Leo One USA demonstrates below how it would make effective use of this recommended spectrum allocation.

The current Leo One USA system design provides the highest service availability of all of the NVNG MSS applicants. Consequently, the Commission's proposed sharing mechanisms has the greatest impact on Leo One USA. Thus, in this analysis Leo One USA is used as a benchmark against which the sharing approach and achievable service availability are measured. The analysis indicates the sharing impact is minimal and acceptable. Table 1 summarizes the Leo One USA system parameters used in this analysis.

Table 1. Leo One USA System Parameters[1].

Parameters	NVNG System
Total No. of Satellites	48
Total No. of Planes	8
Altitude	950 km
Eccentricity	0
No. of Planes	8
Sats. per Plane	6
Inclination	50°
RAAN	0°, 45°, 90°, 135°, 180°, 225°, 270°, 315°
Intra-plane Sat. Spacing	60°
Inter-plane Sat. Spacing	7.5°
Argument of Perigee	0.0°
Orbit Period	103.8 min
Gateway Downlink Channel Bandwidth	60 kHz
Service Downlink Channel Bandwidth	35 kHz

1.2 System A Attributes

The proposed System A uses the combined downlink spectrum of System 1 and System 3. For the uplink it is proposed that the spectrum available for narrowband operation be used equally by System A and System B.

Specifically for the downlink, it is proposed the 400.15-400.505 and 400.645-401 MHz bands will be time shared with the DMSP satellites, and the 400.505-400.5517 MHz band will be time shared with VITA. This sharing will be on a non-interference basis to the DMSP and VITA systems.

[1] At 400 MHz, the necessary channel bandwidth is 35 kHz for the subscriber channels and 60 kHz for the gateway channels due to the higher Doppler guard band requirements at 400 MHz.

For the Uplink, it is proposed the 150.00-150.05 MHz band segment, which is allocated for LMSS (no maritime or aeronautical use), will be time shared with the Russian Navigation Satellite System (RNSS), as well as with land mobile radios in most countries. The 149.81-149.855 MHz band segment will be time shared with VITA, and the 148.905-149.81 MHz band will be dynamically shared with Orbcomm and System B. This sharing will all be accomplished using dynamic channel assignment techniques. The VITA band segment is not shared with System B and the navigation band segment is not shared with System B or Orbcomm, allowing unique spectrum for protected links.

The DMSP MetSat band can be shared on a non-interference basis to the MetSats by using a frequency avoidance concept. This simplified frequency sharing concept requires the Little LEO satellites to step or hop to the opposite MetSat band segment whenever a MetSat coverage footprint overlaps that of a Little LEO satellite horizon. The coincidence times are readily precomputed and frequency selection instructions can be loaded into each satellite to span the duration of element set validity.

DMSP satellite ephemeris information is needed in order to predict the DMSP satellite locations. In order to ensure ephemeris prediction accuracy, weekly updates from DOD/DMSP are required along with the frequency being used by each satellite. It is assumed that the frequencies are not changed often and that weekly updates are acceptable, although more frequent updates could be accommodated.

It should be noted that for a five satellite DMSP system, the potential exists for two DMSP coverage zones to overlap a Little LEO horizon footprint, as shown in Figure 1, over CONUS. These coverage contours were obtained by using five of the DMSP satellites currently in orbit as representative of future orbital coverage. This overlap is assumed to result in total blockage of the Little LEO System in those areas where the dual DMSP overlap occurs (this is a worse case assumption). Any two DMSP satellites within the horizon coverage of a Little LEO satellite will potentially result in a blockage situation. This worse case analysis assumes the two DMSP MetSats in close proximity will use both portions of the band so as not to interfere with themselves, leaving System A without any available spectrum during this overlap period.

Under the assumption that the DMSP downlink frequencies in use will be provided to the Little LEO operator, it is possible to estimate user availability for the band hopping approach described. The availability to Leo One USA users is shown in Figure 2 for System A satellite coverages of 5, 10 and 15 degrees elevation angle and for DMSP coverage of 5 degrees without using the VITA channel. What would otherwise be 100 percent coverage at 40° latitude, if sharing with DMSP were not required, is reduced to approximately 77 percent at 15 degrees coverage as a result of the sharing with DMSP. This availability improves dramatically with the use of the VITA channel.

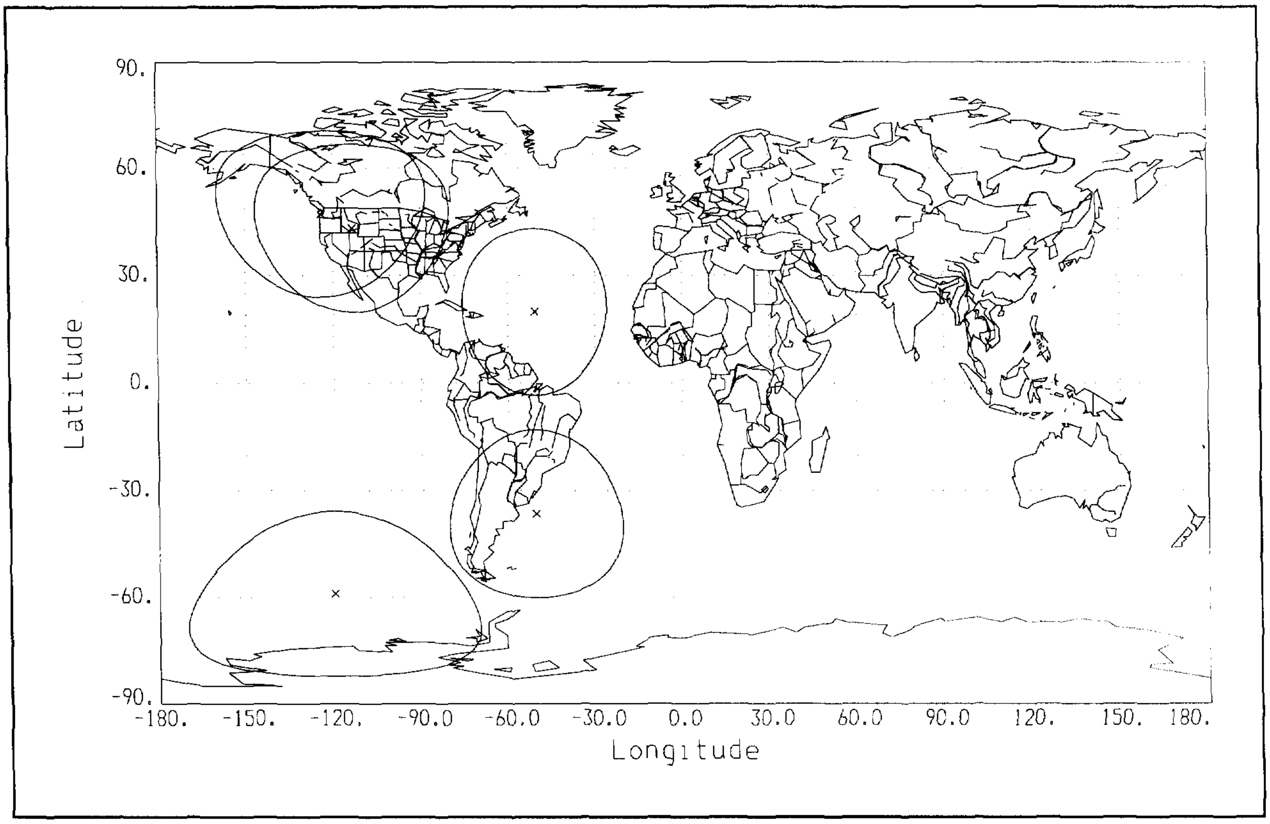

Figure 1. DMSP Five Satellite Constellation Coverage For 5° Elevation Footprint.

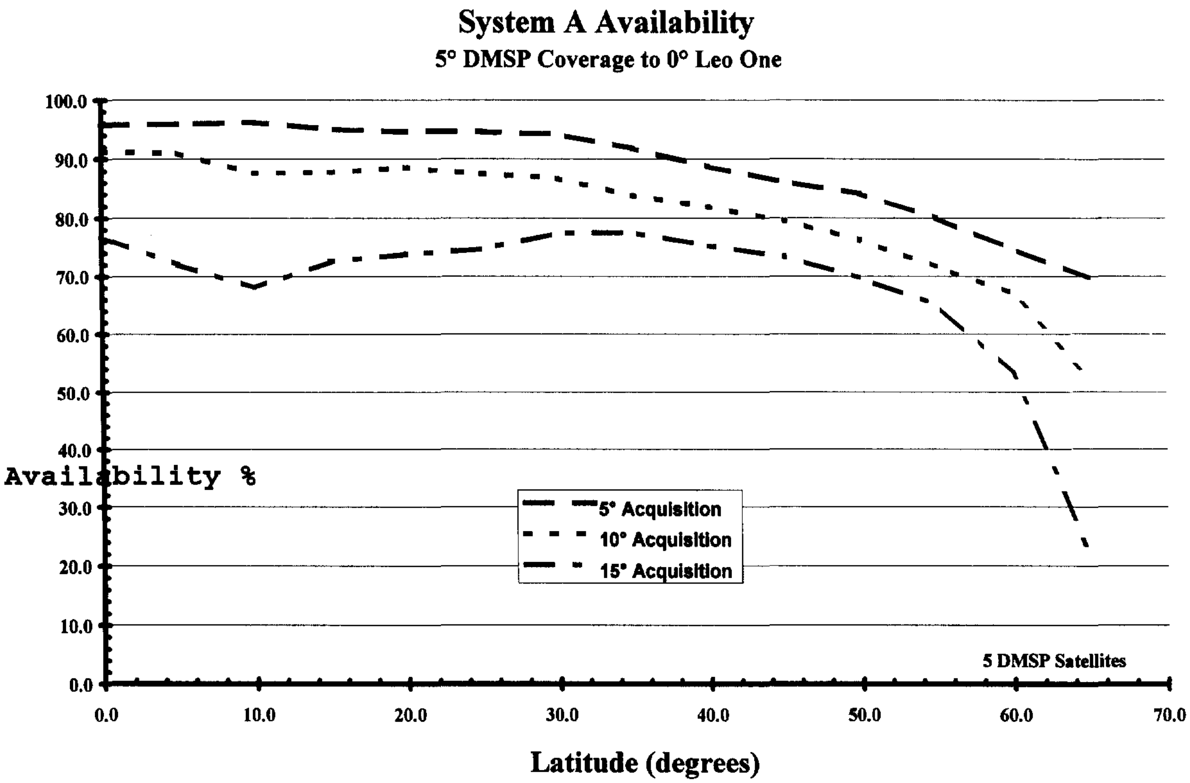

Figure 2. Availability For 5 DMSP MetSats Without Use Of VITA Channel.

In order to increase system availability to near real-time, sharing of VITA's channel is needed to assure a downlink subscriber channel for near continuous availability. The VITA channel is available most of the time since VITA is a one satellite system. This channel is sufficient to support one subscriber channel downlink, thus ensuring 100 percent availability of subscriber usage unless a VITA satellite coverage footprint is also overlapping with the System A interference footprint during a time of a dual DMSP overlap situation. During this occasional occurrence, System A would cease transmission and an outage would occur.

A significant improvement in availability is achieved using this System A allocation. Figure 3 is a plot of the availability for 5, 10 and 15 degrees Leo One USA coverage. The constellation availability at 40° latitude for a 5° DMSP coverage situation is increased to over